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IMPROVING IRRIGATED AGRICULTURE PERFORMANCE THROUGH AN UNDERSTANDING OF THE WATER DELIVERY PROCESS[†,‡,1]

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ABSTRACT

The performance of large-scale irrigation projects worldwide has been disappointing to the international community. Continued poor performance could limit our ability to provide food and fibre for a growing, more affluent world population. Improvement in the productivity of large irrigation systems is a key component to assuring future adequate food and fibre supplies. This paper discusses the reasons for poor performance of these schemes and proposes a method to improve their performance. A main problem is that operation of these irrigation systems is not tied to productivity. As a result, the dispersive nature of these large open canal distribution systems causes extreme variability in water delivery service to users. The remedy is to break the system down at key intermediate locations within the network and to improve physical and administrative control at those locations. Published in 2006 by John Wiley & Sons, Ltd.

KEY WORDS: irrigation systems; irrigation performance; water productivity; irrigation networks; irrigation uniformity

RÉSUMÉ

Les performances des grands projets d'irrigation mondiaux ont été jugées décevantes par la communauté internationale. La poursuite de cette tendance pourrait limiter notre capacité à répondre aux besoins en produits alimentaires et fibres textiles d'une population plus nombreuse et plus aisée. Pour contrer cette tendance, l'amélioration de la productivité des grands systèmes d'irrigation est un facteur clé. Cet article discute des raisons de ces faibles performances et propose une méthode pour les améliorer. Un problème principal est que leur exploitation se fait indépendamment de leur productivité. Ainsi, la nature éclatée de ces grands systèmes ouverts de distribution par canaux explique l'extrême variabilité du service de livraison d'eau aux utilisateurs. La solution consiste à analyser le système en un certain nombre de points clés (nœuds du réseau) et à y améliorer la gestion matérielle et administrative. Published in 2006 by John Wiley & Sons, Ltd.

MOTS CLÉS: systèmes d'irrigation; performance de l'irrigation; productivité de l'eau; réseaux d'irrigation; uniformité de l'irrigation

INTRODUCTION

Expansion of worldwide food production during the twentieth century was closely associated with the expansion of irrigated land, and associated drainage. Yet the international community appears to be nervous about the prospects for the future increases in production that will likely be required to feed an expanding, more affluent world

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population (ICID, 2003). What appeared to be unlimited water resources for the planet are now seen to be limited. Many irrigated areas that were developed with groundwater may not be sustainable. Expanding urban populations are demanding more water from overallocated supplies. In-stream flows for navigation, fish, and other environmental uses are beginning to reduce existing diversions for irrigated agriculture and will reduce the likelihood of future expansion in diversions (Svendsen and Turral, 2006).

Improvements in the performance and productivity of existing irrigation schemes are viewed as an important source for the needed expansion in world food production. I am confident that the international irrigation and drainage community will rise to the challenge.

Over the last several years, ICID had a Working Group on Performance Assessment. They have provided some useful guidelines on assessing the performance of irrigation and drainage systems. A recent issue of the ICID Journal *Irrigation and Drainage* discusses the need for benchmarking of irrigation and drainage schemes (Malano *et al*., 2004a). In general, there are two types of indicators—external indicators of production, water use, or productivity and internal measures of operational performance (Malano *et al*., 2004b). Various methods are available for measuring these indicators, which provide important diagnostic tools to determine how irrigation and drainage schemes are operating (ICID, 2004). However, making a link between external performance and internal performance is not straightforward (Burt and Styles, 1999; Styles and Marino, 2002). Without a clear understanding of the link between irrigation system operations and the resulting system performance, one cannot develop a rational plan for implementing needed changes, nor where to start.

In this paper the nature of large-scale systems and how this perspective influences how one might approach improvements in the productivity of large irrigation and drainage schemes will be discussed.

IRRIGATION UNIFORMITY AND PRODUCTION

In the irrigation industry, high production is the result of uniform production. Uniform production over the land area is required to achieve high gross production and high product quality. One can raise the yield over the entire field, for example when converting from dry-land to irrigated agriculture, or when applying commercial fertilizer. In irrigated agriculture, one typically increases the average yield by raising the yields in the low-yielding areas (Clemmens, 1991). In many cases, the high-yielding areas cannot be substantially improved. Uniformity produces quality and value!

Unfortunately, all field irrigation systems are non-uniform, regardless of what equipment salespeople may claim. If the irrigator supplies an amount of water that exactly meets the crop water need, roughly half the field will be underirrigated and half the field will be overirrigated. When an insufficient amount of water is supplied to one portion of the field, the influence on yield is relatively obvious, and somewhat predictable. For some crops, yield is nearly a linear function of water consumed (Doorenbos and Kassam, 1979; Solomon, 1983). The usual response of farmers to insufficient water over one part of a field is to supply more water to the field as a whole, assuming it is available (Clemmens, 1991). This will increase production on that part of the field, but will result in more overirrigation in other parts of the field. The influence on yield of supplying too much water to a portion of the field is less obvious. In fact, the impact may occur on another area of the field where drainage water collects or even on a neighbour's field.

An alternative approach to increasing yield is to improve the irrigation uniformity. This increases the yield in the area of the field that was underirrigated and increases the average yield with a given amount of available water. Improvements in uniformity also decrease the chance of yield reductions due to excess water. Successful producers make irrigation uniformity a priority.

There are significant parallels with this concept in the delivery of irrigation water. Irrigation water distribution is never perfect. If water supplies are just adequate to meet the water demands, roughly half of the users will get less than their share and half will get more. Again, the common approach is to increase the total amount of water supplied to the system so that a larger fraction of users get the amount of water needed (Clemmens and Bos, 1990). If the increased water supply is not available, users are just told that the water supply is inadequate. Poor distribution of water to users will nearly always lead to less production for the system as a whole, similar to the farm-field analogy. An alternative approach is to improve the distribution of water so that all receive an amount that is closer to their fair share. This is easier said than done.

CHAOS AND LARGE-SCALE SYSTEMS

If we want to make meaningful improvement in the productivity of irrigated agriculture, there are a few characteristics of large-scale systems that are important to understand. Let us start with an analogy to physics. For centuries, Newtonian physics has been successfully used to build skyscrapers, launch rockets, build dams, convey water, etc. At the large scale, the world appears predictable and orderly. However, quantum mechanics shows us that at the very small scale, everything appears random and chaotic. Within a field, every square centimetre of surface has a different soil texture with different fertility, every plant has a different genetic vigour. Even rainfall is not uniform. The addition of irrigation water, fertilizers, and other amendments may add additional variability. For irrigation, there are a large number of factors that cause irrigation systems to be non-uniform. Successful farmers learn how to deal with the inherent variability of agricultural production and, more importantly, how to overcome it.

How does this apply to the management and operation of irrigation systems? First, one has to realize that the amount of water supplied and the quality of service to users are variable. This is true for the best built and best operated systems, as well as for poorly performing systems. The difference is just in the degree of non-uniformity in service. What is important, however, is the impact that the variability in water supplied and in delivery service have on production.

Consider an irrigation water conveyance and distribution system that is reasonably well designed and constructed. An organization is developed to oversee operations and an operating plan is developed that is consistent with the original intent to supply water. Is this sufficient to assure reasonable productivity and a sustainable system? Of course the answer is no, but let us examine the various aspects of this system to see why.

At the large end of the system, operators are expected to maintain water levels and flows at the desired values. Keeping water levels constant is relatively easy to judge, compared to flow rates, since flow rates can be difficult to measure accurately in large canals, particularly on a continuous basis (or at intermediate check structures). For many systems, flow changes are relatively seldom. But operators may have to respond to disturbances, for example storm runoff entering the canal, weeds and debris clogged in gates, changes in diversion conditions. If conditions deviate from target conditions, the operators are trained to return them to the desired state. On a well-managed scheme, operator performance is tied to their ability to maintain the desired conditions. These disturbances at the higher level cause unintended consequences at the lower level. What appear to be minor problems at the top of the distribution system can end up as extreme differences in delivery—or chaos—at the bottom. I define chaos as anything that causes the processes within a system to be variable and difficult to predict.

Note that the amount of chaos at the bottom of a delivery system is not necessarily the result of a poor management structure, poor supervision, or inadequate infrastructure. The second law of thermodynamics says that the entropy of an isolated system cannot decrease, where entropy is a measure of randomness, variability, or chaos (Reynolds and Perkins, 1970). Energy must be added to the system to ensure that disturbances at the top do not propagate and grow as they move downstream. This does not refer to energy in terms of power requirements. In this case the energy may be management effort, communications, or even the energy required to bring about physical infrastructure changes.

Some irrigation distribution systems implement a static operating plan. These systems may be referred to as water disposal systems. The mindset of operations is to deliver the irrigation water and, in effect, dispose of it. There is no thought regarding the production that comes from this water, nor whether the delivery has any influence on its effective use. Under such systems, there are no incentives for management or operators to improve delivery performance under the current operating plan, let alone to devise new, more flexible operating plans that allow farmers to be responsive to market conditions. Without some outside influences, such systems are doomed to perform poorly.

There are a number of distribution systems that have been developed to simply divide the available supply, primarily based on physical structure controls (e.g. Malhotra, 1982). However, it is not sufficient to simply release water from the top and assume it will be distributed according to the plan. There are far too many things that can alter where the water ends up. Without sufficient water accounting, such a strategy will not result in high productivity.

A classic example of the entropy principle is the need for maintenance. It is well known that significant energy, through maintenance, is required just to keep the current level of performance. Without maintenance, these systems will degrade to their naturally chaotic state. Maintenance should be viewed from the perspective of avoiding chaos. The issue here is that the cost of maintenance is often not considered in the operating plan and budget. No one really wants to pay for maintenance. But it is a business necessity. The biggest hurdle we have to face with maintenance of irrigation distribution systems is that no connection has been made between the quality of service and the cost of operation and maintenance.

The sustainability of irrigation and drainage enterprises depends on the farmers' ability to control their own destiny (Merriam, 1987). In arid environments, farmers can only control their own destiny if they have reasonable control over their water supply. Without a reliable water supply, farmers are at the whim of the chaos that is inherent in large-scale water-delivery systems. This explains why farmers are willing to invest in tube wells that are under their control. There are other issues with tube-well systems and associated groundwater/conjunctive-use management, but they will not be discussed in this paper.

ILLUSTRATIVE EXAMPLE

So far in this paper, a number of claims have been made that may be hard to defend. An example will help to illustrate these points. Consider a large irrigation water canal distribution system. The main canal serves 200 000 ha. Water from this canal serves primary (sub-main) canals that each serve 20 000 ha. These, in turn, serve secondary canals that each serve 2000 ha. Each secondary canal serves tertiary canals that each serve 200 ha, which serve quaternary canals that deliver water to 20 ha quaternary units. Water within a quaternary unit is distributed to individual fields, bays, or irrigation sets, one at a time. The field irrigation system distributes water to plants within each bay. Because we are interested in productivity, it is important to take the distribution of water all the way down to the plant scale. A diagram is shown in Figure 1. Real irrigation distribution networks are much more complex, but this simple example is suitable for illustrative purposes.

It is assumed that the distribution network includes check and offtake structures and gates that can be used to distribute the water among canals. This is an open canal system operated by gravity only, with water supplied from an upstream reservoir. The system is assumed to be in reasonable condition. Each canal is operated manually by a canal operator. These operators are reasonably well trained and experienced. A management system is in place such that operators have reasonable performance targets. Farmers receive water at the quaternary (20 ha) or field level.

In order to understand how these systems actually function, we have to analyse how water flows through canals. Water released at the head of the canal takes time to reach users at the bottom end. A change in flow at the head may arrive days after it has been released from the top. A sudden flow change upstream passes through the canal as a wave, which disperses as it travels downstream. The wave travel time and dispersion are influenced by the

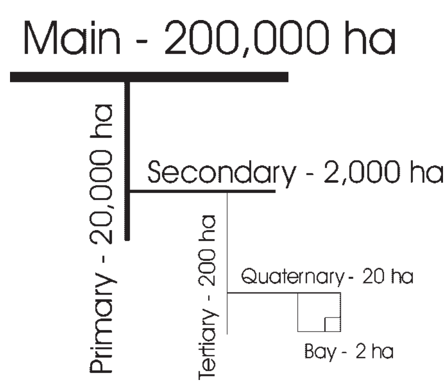

Figure 1. Diagram of example canal network, showing only one canal at each level

conditions in the canal, which change over time, and by the characteristics of each canal structure that the wave travels through. Operators at the top can make one change in gate position at one time to implement a new schedule. Operators further down the system must often make multiple changes in gate positions to implement the same schedule change because the change in flow arrives gradually.

Research studies and experience have demonstrated that it is not possible for canal operators with this type of system to provide perfect distribution of water to offtakes from their canal (Palmer *et al*., 1991). In the example, the offtake from one canal is the headgate for the next lower canal or the quaternary unit. Flow measurements at gates are never perfect. Timing of flow changes is never perfect because canal wave delay times and dispersion vary over the season. The result is that some offtakes will receive more than their share and others less than their share. For this simple example all offtakes should get the same amount of water, but do not. There are methods to deal with situations where offtakes should get different amounts of water (Clemmens and Bos, 1990), but we will not go into that level of detail here. We can describe the variation in the amount of water received with standard statistical parameters, such as the standard deviation. Putting this in relative terms, the standard deviation is divided by the mean or average amount to give the coefficient of variation, which is often given as a percentage.

Based on observation, a reasonable estimate for the coefficient of variation for the distribution of water from a canal to offtakes is 10% (Bos *et al*., 1991; Palmer *et al*., 1991). This should be an achievable target for a distribution system that is reasonably well constructed and has reasonable management, as discussed previously. This will provide an amount of water that is within 10% of the average amount for roughly two-thirds of the offtakes. Water to nearly all the offtakes will be within 20% of the average.

Figure 2a shows the distribution of water from the main canal to the sub-main canals. Half get more than average, half get less. The distribution shown here is a normal distribution, for illustrative purposes. Now, each sub-main distributes water to secondary canals. Each sub-main has a different amount of water to distribute, and the fraction of its water that it provides to each secondary canal varies around this amount. Here, we assume that the coefficient of variation of the distribution of water from sub-mains to secondary canals is also 10%. We then use statistical methods to estimate the distribution of water to all secondary canals for the system as a whole. These methods are called combination of variance techniques (Mood *et al*., 1974; Clemmens and Molden, 2006).

Figure 2b shows the distribution of water to secondary canals. The heavier line is the distribution to secondary canals and the lighter line is the distribution to sub-mains. Note that the secondary canal distribution has a lower peak, which means that fewer secondary canals receive a supply that is close to the average amount, and the curve is spread wider, which means that more secondary canals receive a supply that is far from the average amount.

We can continue this analogy and examine the distribution of water to tertiary and to quaternary canals. If we assume the same coefficient of variation at each level, from Figure 2c and 2d we see that the distribution curve continues to spread out. The quaternary canals distribute water to individual irrigated units, generally one at a time. Even at this level, there can be a significant variation in water applied to individual irrigated units, so we assign the same coefficient of variation to this distribution as was assigned to canals (Figure 2e).

Next, it is assumed that the field irrigation systems have a coefficient of variation of 20%, corresponding to a distribution uniformity of roughly 0.75. Combining the within-quaternary-unit distribution and in-field distribution with the distribution of water from the canal system, we can construct an estimate of the distribution of water to plants for the system as a whole (Clemmens and Solomon, 1997; Clemmens and Molden, 2006). This is shown as the heavy line in Figure 2f. Note that this distribution is relatively wide, with about 8% of the plants receiving less than half of their share of the water supply. Note that for this simple example we assume that all plant areas have the same demand for water, again for simplicity.

Now let us get back to the real world. We also have to consider water that is lost to the system. This water might be recoverable downstream from the system, but for our purposes it is considered lost. Some water is lost at each level within the system. Oftentimes, water is unaccounted for because too much is distributed to offtakes. Here we are only concerned with that water which leaves the system, for example evaporation, uncollected canal seepage, unrecovered spills, and unrecovered tailwater from fields. (It does not include field deep percolation.) For illustrative purposes, we assume that 5% of the water that enters is lost at each level within the system. This example has six levels, so roughly 26% of the water is lost (that is 1 minus 0.95 raised to the sixth power). The effect of these water losses on the distribution of water is shown in Figure 3. The distribution is shifted to the left significantly, indicating that plants are receiving less than their share of the water supplied, even on average.

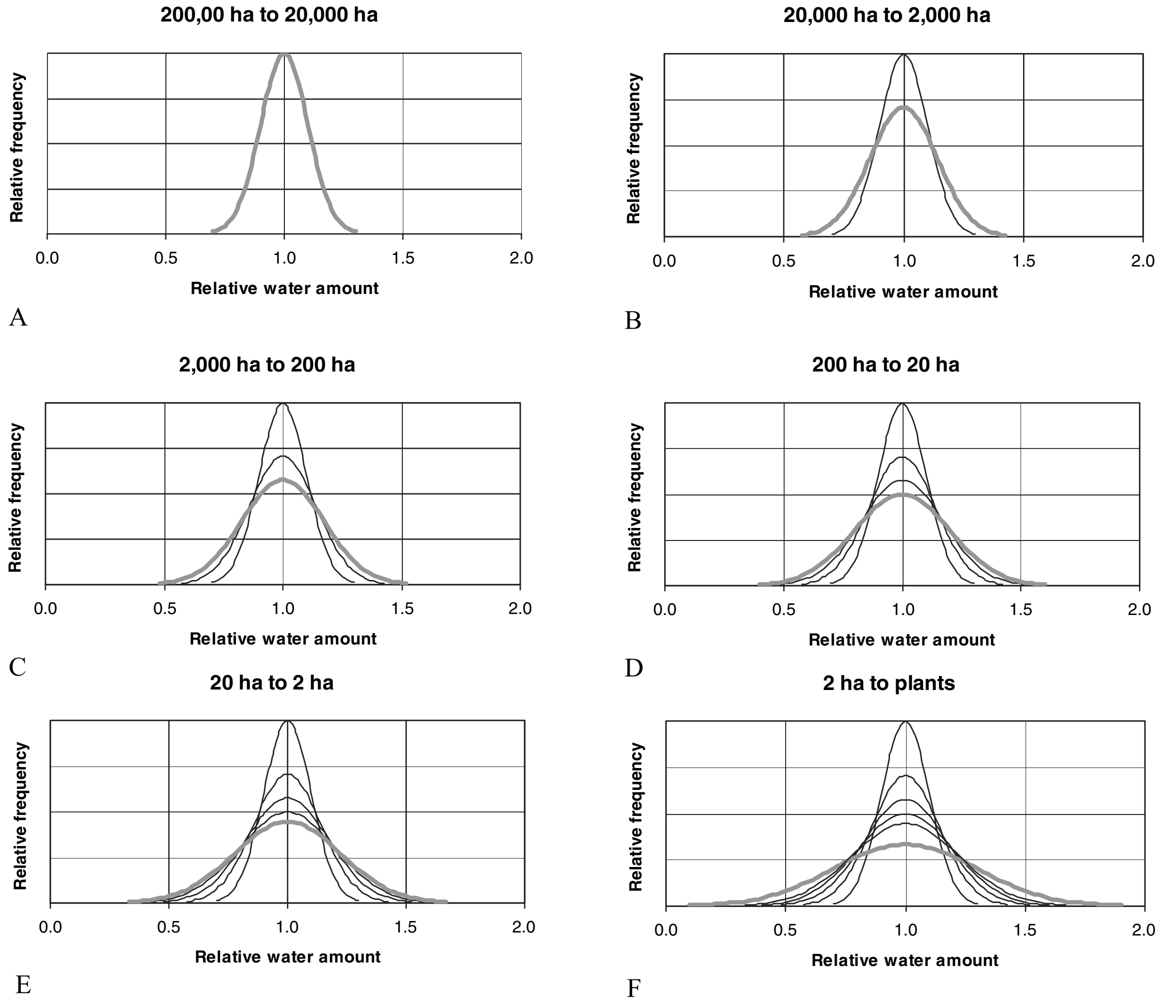

Figure 2. Distribution of water at various levels within an irrigation system. (Hypothetical example)

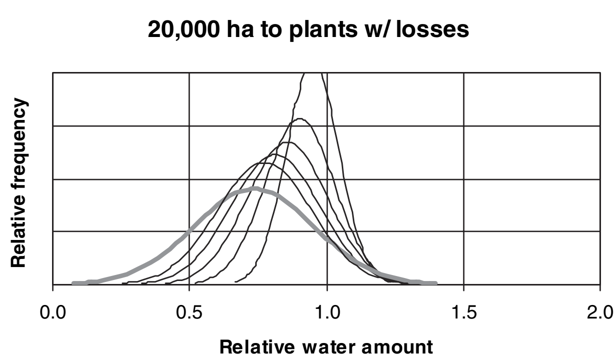

Figure 3. Distribution of water within irrigation system with losses

So far, the results have been presented as a function of the amount of water supplied. It would also be useful to examine these results as a function of the water required by the plants. The previous graph (Figure 3) had losses of 26%. In order to overcome these losses, a relative amount of irrigation water (RIS) of 1.36 (1.0/(1 – 0.26)) would have to be supplied. If enough water were supplied to overcome these losses, an amount of water would be supplied to the irrigated units that just matches demand, as shown in Figure 4a. Note that with this amount of water, half the plants receive too little water while half receive too much. For this example, 10% of the plants would have less than 50% of the water needed. With a yield–water use relationship, one could use the distribution shown in Figure 4a to estimate relative production for the system as a whole.

The usual response to this situation is to supply additional water. If twice the amount of water needed by the plants (RIS = 2.0) is supplied, the distribution of water to plants within the system based on the assumed distribution and losses would be as shown in Figure 4b. The same scale is applied on these figures for comparative purposes. Note that with losses, the average amount of water supplied to plants is about 1.5 times the amount needed.

Let us summarize what this example means. We have a gravity irrigation system that is in reasonable condition and has reasonable management. Yet, more than half the water supplied to this system does not contribute to production (this means that the system irrigation efficiency is less than 50%). At the same time, more than 20% of the cultivated area is underirrigated. Half of the cultivated area receives more than 150% of the water needed and 20% of the cultivated area receives more than twice the water needed. These all contribute to potential waterlogging and salinity. Chaos dominates such large-scale gravity irrigation water distribution systems. These systems are naturally dispersive, which makes control difficult.

A major point here is that: these results are what one would expect for a large-scale open-channel water distribution system, even one with reasonable infrastructure and reasonable management. In general, these results should be expected. Many systems in the world today are much worse. Poor design, poor maintenance, and poor operations all make the distribution and losses worse. Time also tends to degrade these systems naturally.

IS IMPROVED MANAGEMENT THE ANSWER?

Back in the 1970s and 1980s, there was a school of thought that put forth the idea that improved management could solve all problems and make any business, including irrigated agriculture, profitable. A good deal of effort, internationally, was put into improved irrigation system management (e.g. Jones and Clyma, 1988). We now believe that many such efforts were marginally successful. We may not expect that improving management control alone will significantly improve the productivity of these systems. It may result in small incremental improvements, but not substantial gains.

Take for example a primary canal operator. Something happens during his shift that results in some extra waves travelling through his canal. It takes a while to get the canal back under control, but by the end of the shift, things are more or less stable. From a management standpoint, the operator has done everything that is reasonable to expect.

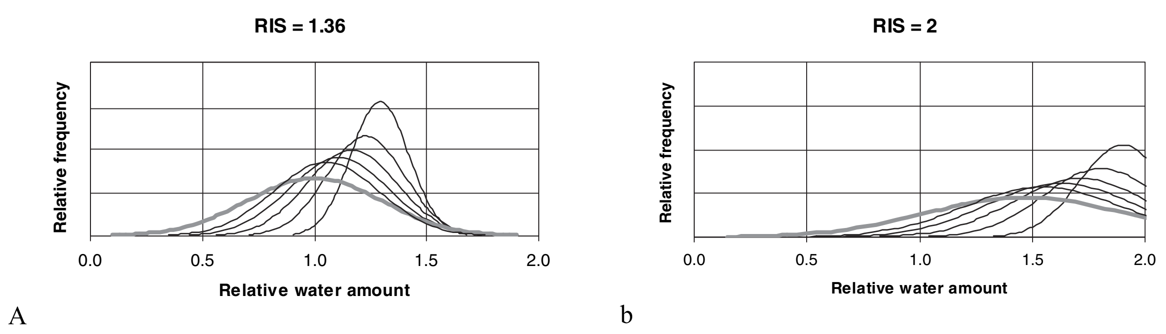

Figure 4. Different irrigation system water distributions for different relative irrigation water supplies (RIS)

Yet the result, when it ripples down through the system, is chaos. One farmer may receive extra water that saves the crop, while another does not get water at a critical stage and has total crop failure. Yet the operator who caused this chaos has performed acceptably.

IS WATER MEASUREMENT THE ANSWER?

Our ability to measure irrigation water has improved dramatically in the last several decades. Computer design and calibration of as-built dimensions have made flumes and weirs the device of choice for irrigation flow measurement because of cost and simplicity (Clemmens *et al*., 2001). Flumes and weirs are very simple and extremely cost-effective (Wahl *et al*., 2005). Even so, there are some locations where flumes and weirs are not suitable. A variety of ultrasonic devices are becoming more and more useful for water measurement in problem situations (e.g. Styles, 2005). These are particularly applicable for large flows because of cost. There are no valid excuses for not providing good water measurement at key locations within a distribution network, for example at canal and offtake headings.

Ideally, water deliveries to all users (or at least quaternary units) should be measured and continuously monitored. This is cost prohibitive for most irrigation systems. However, it is difficult to develop effective management controls without appropriate feedback on operational performance. That is the situation in many systems today. The infrastructure is often not in place to allow good internal control of water delivery operations. Water measurement is a key component of water control, but it is not sufficient for significantly improving productivity by itself.

CHANGE MANAGEMENT PHILOSOPHY AND CONTROL INFRASTRUCTURE

The answer is to change the management philosophy. The system that was described has a bureaucratic philosophy. Each operator at each level has performance criteria that can be objectively evaluated. Each operator has little or no control over the fluctuations that occur from above, and must simply deal with them. There is no link between water-delivery operations and production. The only way to overcome this scenario is to re-establish physical control of the water at intermediate points within the system. Positive physical controls are needed to isolate lower parts of the network from upstream disturbances and chaos. Administrative controls are one way to force improved physical control. Administrative controls include the establishment of delivery criteria that are agreed upon by both the supply and demand sides. This includes flow rate, volume, flexibility, etc. The water supply side must be held accountable for the agreed-upon service and the water users side must be willing to pay for the service. This is in effect a contract. Water measurement and monitoring are important for documentation. The most important aspect of this new administrative control is that purposeful corrective actions must be taken—not only to remove the chaos, but to reverse its effects. If the flow rate to one offtake is low today, it should be high by the same amount tomorrow (if that is an appropriate correction). It is not sufficient to return to target conditions. The chaos needs to be reversed. This is a service philosophy.

Developing the required physical controls will require infrastructure changes that are consistent with the new management philosophy. This service philosophy is needed to guide the process of infrastructure improvement. Some projects have begun significant infrastructure changes without first adopting an appropriate management philosophy. As a result, costly improvements may not have had the desired impact on productivity.

A logical place to re-establish water control is at all places where the water is already transferred from one administrative unit to another. In the United States, there are typically two key locations where water control changes hands administratively: (1) where conservancy districts or government agencies transfer water to irrigation districts and (2) where irrigation districts transfer water to farmers. For comparison to the example given here, this occurs at the primary and tertiary canal levels, as shown in Figure 5. When water is delivered to an irrigation district, the amount of water delivered and its variability are under relatively tight administrative control, in most cases. It is up to the water supplier to adsorb any variability and to find ways to provide the agreed-upon service. The farmer deals with water control below the farm offtake. Delivery rules force the irrigation district to provide an established level of performance to farmers. Farmers have a voice in irrigation district operations through an elected

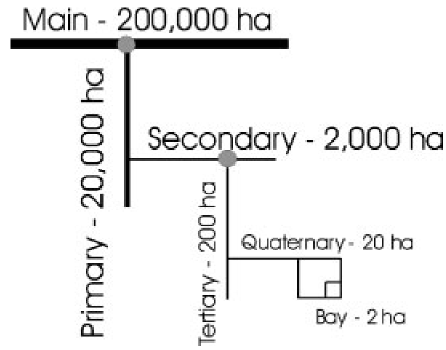

Figure 5. Points of administrative and physical control in typical US irrigation systems

board of directors. Any variability in the system upstream from the farm must be dealt with by the irrigation district. To the extent possible, chaos is not passed on to the farm level. These administrative controls force the needed physical and operational controls to be implemented.

For many lesser developed countries, water user associations (WUAs) are being established to provide more local control over water (e.g., series of papers in Svendsen *et al*., 2005). These local organizations often consist of a group of farmers at the secondary or tertiary level. The intent is to allow the users to have an influence on how their water is distributed. The heading of a secondary canal is often the location where WUAs take over control of the water. So, this is a logical place to re-establish physical control, as shown in Figure 6. Along with this administrative change, it is absolutely imperative to re-establish physical control of the water. WUAs often do not have adequate control over their supply of water. They remain at the whim of the chaos from the main part of the water distribution system. It is often not possible to implement control in the middle of the system. If the water is not there, there is little, if anything to control. The WUA may be too far down the system for local infrastructure changes to improve control.

Water suppliers need to be made accountable for water volume supplied to WUAs and more flexible in responding to changing demands over time. This may require substantial infrastructure improvements within the upper part of the delivery system. Without these improvements, such systems will continue to be subject to chaos, and WUAs will not have a fighting chance. In addition, WUAs often lack the training and finances to make meaningful improvements in their infrastructure, operations, and service to users. Many of these systems were turned over to WUAs in a poor state of maintenance. Regardless of the ongoing struggles to make WUAs economically viable, they are a positive step in the right direction toward farmer self-reliance.

Figure 7 shows the impact of re-establishing control at the head of the secondary canal in the example. Here, control at the secondary canal heading is assumed to give a standard deviation of 5%. Overall system losses are

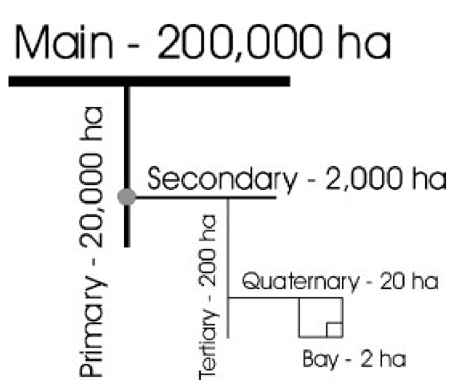

Figure 6. Points of administrative and physical control recommended for irrigation systems with water user associations (WUAs)

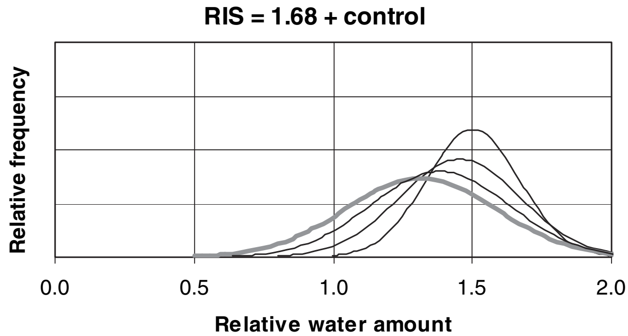

Figure 7. Water distribution for irrigation system with re-establishment of control at the head of secondary canals

assumed reduced by 5%. An improvement in field distribution uniformity is assumed, resulting from the improvements in delivery service. The contrast between the water distribution to plants (lower heavy lines) in Figures 4b and 7 is striking. To provide roughly the same amount of deficit, one only needs to provide half of the additional water required to overcome distribution issues (that is, halfway between RIS = 1.36 and RIS = 2.0). This results in less water diverted, much less overirrigation, and less potential for waterlogging and salinity problems.

So far, only service to existing cropping systems has been discussed. Farmers need flexibility in order to grow a wider variety of crops and respond to market demands. This adds to irrigation system productivity by raising the value of the crops produced. However, there is a trade-off between flexibility and control. As farmers demand more flexibility, control becomes more difficult because the changes in canal flow are larger and more frequent. Chaos grows. Irrigation districts in the US are looking at improving water control and flexibility at the farm delivery point (tertiary level) by improving control internally within their systems. The most logical place to re-establish control for these purposes is at the head of secondary canals. Common methods are flow rate control at the headgates of secondary canals and regulating reservoirs, there or slightly downstream, to buffer upstream disturbances and allow more flexibility. These are considered internal controls. In the long run, water control should be re-established at every level within the distribution network.

Our knowledge of irrigation canal control has improved substantially over the last decade. Supervisory control and data acquisition or SCADA systems are now affordable and cost-effective for nearly all irrigation distribution systems, large and small (Burt and Anderson, 2005). With these advances in electronics and communications, and in canal control theory and methods, significant improvements in canal control are now possible with minimal cost and infrastructure changes. It is time for irrigation to join the information age.

IMPORTANT STEPS FOR IMPROVING PRODUCTIVITY

A series of steps to be taken to improve the performance of irrigated agriculture is provided below. The steps themselves are not really new. However, there is a subtle difference in focus, based on the analysis of the distribution process.

Step 1: *Identify the causes of chaos and barriers to high productivity*:

- Identify the water supply needs of agricultural producers—current and future (demand);
- Identify other constraints to high production;
- Identify the current institutional framework and the water supply rules;
- Identify current conditions of water supply availability and water delivery service (supply);
- Identify the current level of water measurement, accounting, and water controls;

- Determine how the water supply rules, water supply availability, water controls, and water delivery service influence production (this is very difficult).

Step 2: *Develop a new management philosophy, and the appropriate institutions, that can implement mechanisms for raising productivity—by removing chaos—by re-establishing control at intermediate points*:

- Identify intermediate points within the distribution network where physical and/or administrative control of water should be re-established—to remove upstream chaos;
- Develop a plan for re-establishing water control, incrementally;
- Capacity building may be important here.

Step 3: *Develop the physical control needed to remove chaos*:

- Modernize the infrastructure;
- Implement new operating criteria and procedures.

SUMMARY

In summary:

- Chaos dominates large-scale open-channel water conveyance and distribution systems;
- This chaos has a direct and negative impact on productivity;
- Low productivity of irrigation systems is seldom the result of poor performance by individuals at any level, but reflects systematic flaws in the overall management approach;
- For bureaucratically managed systems, management improvement alone will not significantly reduce this chaos;
- A change in management philosophy is required to overcome chaos;
- Both administrative and physical controls are needed at intermediate points within the distribution network;
- Energy, in terms of management effort, infrastructure improvement and associated funding, is required to re-establish water control and raise productivity;
- New technology for water measurement and control is available that can aid in efforts to significantly improve the productivity of irrigation systems;
- The time is right for the international irrigation and drainage community to step forward and promote positive change in irrigation productivity. Please join this effort.

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